FIELD HARMONICS OPTIMIZATION OF THE NSLS II STORAGE RING MAGNETS

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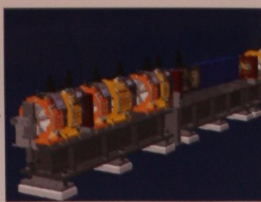NSLS-II, Brookhaven National Laboratory, Upton, NY 11973 U.S.A.

Abstract

The NSLS-II storage ring lattice magnets have stringent field harmonics requirements in order to achieve its performance requirements for beam emittance, dynamic aperture, and beam life time. Approximately 1000 of these magnets were built with very tight machining and assembly tolerances of the order of 10 μm. The pole profiles and shimming of the poles were guided by 3-D nonlinear magnetic field analyses. Various field anomalies found during the magnet production were also identified and corrected by detailed 3-D field analyses and magnetic measurements. In this paper we present case studies of various field harmonics optimization for the NSLS-II magnets

Introduction

The National Synchrotron Light Source II (NSLS-II) under construction at Brookhaven National Laboratory will be a state-of-the-art 3 Gev electron storage ring designed to deliver world-leading intensity. The 792-meter circumference storage ring is comprised of quadrupoles, sextupoles, dipole and corrector magnets. All magnets were built to harmonic specifications. The magnet program entailed measurements at the vendor or BNL and necessitated the need for shimming and/or chamfering to meet the specifications.

Fig. 1 NSLS –II Girder Assembly

Table 1. Magnet Allowed Harmonic Specifications

Description	Quad. 66mm	Quad. 90 mm	Sext. 58 mm	Sext. 76 mm	Dipole 35/90 mm	Corrector 100/156 mm
Good Field Region/Radius [mm]	25	25	25	25	±20 Hor. ±10 Vert.	±20 Hor. ±20 Vert.
Field Homogeneity [x10⁻⁴]	-	-	-	-	5	100
Harm b6 [x10-4]	±3	±0.5	-	-	-	-
Harm b10 [x10-4]	±3	±0.5	-	-	-	-
Harm b14 [x10-4]	±3	±0.1	-	-	-	-
Harm b9 [x10-4]	-	-	±1.0	±0.3	-	-
Harm b15 [x10-4]	-	-	±0.3	±0.3	-	-
Harm b21 [x10-4]	-	-	-	±0.5	-	-

Perturbation Studies

2-D perturbation studies of the 68mm sextupole and 66mm quadrupole were done to determine machining and assembly tolerances. Three sets of points that comprise the pole profile were perturbed to simulate manufacturing errors.

- The delta in harmonics from the base case are listed in Table 1b.
- Out of spec harmonics are highlighted.
- 10 microns of pole profile variations provide acceptable field performance.

Fig. 2a)Sextupole profile   b)Perturbation points

Table 2. Harmonic delta from Perturbation results

Machining Methodology

Traditional magnet fabrication techniques employ the following operations: lamination stamping, yoke stacking and bonding and magnet assembly. Magnets produced using this sequence achieve a mechanical precision of 50-100 microns. .

To meet the specifications, the iron quality, machining, and assembly tolerances are crucial in determining the final harmonics.

The secondary manufacturing processes used to achieve the field harmonics were:

- Machining the interface surfaces of top and bottom yokes to provide a precise flat mating interface.
- Assemble yoke halves using an established bolt torque and tightening sequence for consistent alignment.
- Final machining of the pole profiles after bonding to eliminate variations from lamination production and yoke stacking process.

Table 3. Achievable tolerances for various manufacturing processes .

Manufacturing Process	Achievable Tolerances (Microns)
Conventional Blanking	20-25
Fine Blanking	10-15
Laser Cutting	50-100
CNC Machining	10
Wire EDM	5
Mechanical Assembly	5-10

Dipole Matching

The 35mm dipole design is unique. A 'nose' was added to the end of the yoke to for the following:

- Save radial space
- Increase the integrated field.
- Used to match the lower order terms and the integrated field between the 35mm and 90mm dipoles.

Fig 3. 35 mm dipole with 'nose'

An Opera study was done to match the harmonics between the 35 and 90 mm dipole using a nose chamfer. Chamfer sizes up to 25 mm and angles up to 5 degrees were studied.

the chamfer angle will adjust the quadrupole component

straight chamfer adjusts the sextupole component

Fig 4. 'Nose' with chamfer

35mm Matching Methodology

- A chamfer was added to match the 90mm quadrupole and sextupole terms.
- The integrated field was measured.
- The length of the nose would be shortened to match the integrated strength of the 90mm dipoles.

Results of Matching

The quadrupole and sextupole terms of the 35mm and 90mm dipoles were the same magnitude. The contribution from the edge focusing were deemed close enough so that the nose did not have to be chamfered.

Fig 5. a) b6 vs Angle   b) b9 vs Angle

Table 4. Quadrupole and sextupole terms due to edge focusing.

35 mm Serial Number	b2	b3	90 mm Serial number	b2	b3
41	1.010506E-03	-1.29775E-04	1	9.81261E-04	1.15642E-04
42	9.66878E-04	-1.34188E-04	2	9.93064E-04	1.21457E-04
43	9.77768E-04	-1.55388E-04	3	1.13684E-04	1.28672E-04
44	8.51758E-04	-1.37700E-04	4	1.06556E-03	1.39277E-04
45	9.30409E-04	-1.33789E-04	5	9.63076E-04	1.22262E-04
46	9.65679E-04	-1.21721E-04	6	9.69447E-04	1.14974E-04

Multipole Chamfering/Shimming

Chamfering and shimming of the multipoles were done if the magnet did not meet specifications.

Fig. 6. Shim locations a)   b)Quadrupole

Table 5. Shim and adjusted harmonics

Shim Location	Adjusted Harmonic Quadrupole	Adjusted Harmonic Sextupole
Center pole	-	b5, a4
Hor. Side Shim	b3, b4	-
Vert. Side Shim	a3	-

Chamfering minimized the first allowed harmonic (b9) in the sextupole and b6 in the quadrupole.

- A tip chamfer will drive the b6 or b9 positive.
- A 'pole' chamfer will drive the b6 or b9 negative.

The pole chamfer is used first to obtain a slightly negative value of b6 or b9, then the tip chamfer is added to zero b6 or b9.

Fig. 7. a) Pole chamfer   b) Tip chamfer

Field Anomalies
35 mm Dipole

A large field variation of about 3 gauss in the beam direction was found.

Fig. 9. By vs Z and bolt hole pattern   Fig. 8. 35mm dipole steel

Mild solid steel plates

Possible causes for anomalie were ruled out:
- machining error
- steel laminations
- packing factor
- stacking process
- welding along the length

- Opera models with a gap between the plate and laminations showed a drop in field of about 1-3 gauss.
- Variation due to the material was 3 gauss.
- The conclusion: the bolting of the top plate to the laminated yoke produced gaps between laminations and plate along with the variation of magnetic properties of along the length.

Fig. 10. By vs Z with plate gap.

Harmonics Optimization
Quadrupole Asymmetry

There was a large b6 variation with current. Modeling showed yoke saturation as the cause. The top and bottom of the yoke were thickened and the magnets lengthened 20mm. Pockets were added to baseplate to increase yoke thickness. The decrease in operating current brought the saturation down to a level of 3-4%.

Fig. 11. Quadrupole yoke

Quadrupole a3 variation with current

The a3 harmonic varied with current. Modeling confirmed that the cause off this was the asymmetry produced by the steel baseplate.
Calculations showed a 3mm shim would isolate the yoke and baseplate.

Fig. 12. a3,a5,a7 vs shim

Quadrupole Machining Error

The quadrupoles produced by a vendor showed an upward trend of b8 from 0.2 to 1.5 units.

Perturbation results showed the b8 could be from an asymmetry in the poletip.

An aluminum pole piece was cut and measured with a CMM.

The vendor discovered the five axes milling machine had an offset of 50 microns. When two of five axes were fixed, the offset disappeared.

Using this machining technique, the b8 was successfully reduced to the 0.2 unit range.

Fig. 13. b8 vs Serial No.

Quadrupole b6 Trending Upward

Halfway through production of the quadruples by a vendor, a sudden jump in b6 was found. (See Fig.14) The chamfers was measured. The design value was 7.2mm. See Table 6a.

The technique used to machine the chamfer was incorrect. The chamfer length varied with yoke length. The vendor changed the method which resulted in the correct chamfer being machined. See Table 6b.

Fig. 14. b6 vs Current

Table 6. Chamfer lengths a)before   b)after machining technique corrected

MAGNET	TOP LEFT	TOP RIGHT	BOTTOM LEFT	BOTTOM RIGHT
Chamfer [mm] 9809 #5	7.58	7.58	7.35	7.48
Chamfer [mm] 9812 #5	8.20	8.18	7.64	7.82

MAGNET	TOP LEFT	TOP RIGHT	BOTTOM LEFT	BOTTOM RIGHT
Chamfer [mm] 9809 #10	6.00	6.05	6.05	6.00
Chamfer [mm] 9812 #10	6.00	6.05	6.05	5.95

Quadrupole Wrong Chamfer Size

The vendor produced 20 yokes with the wrong chamfer size because of the machining error.

The chamfer size had to be reduced to drive the b6 lower but this was now impossible on the already-machined yoke.
The solution was to use a 1.5 mm 'pole' chamfer to reduce the b6 harmonic.

Skew Quad

A very large skew octupole term was found in the combined function skew corrector.
An Opera model verified the measured results.
The width and position of the quad coils, the number of turns,and the wire size were run in various model configurations.
New coils were designed and tested, reducing the skew octupole from hundreds of units down to less than 50.